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MAGNETIC FIELD MEASUREMENTS OF 1.5 METER MODEL SSC COLLIDER DIPOLE MAGNETS AT FERMILAB

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Abstract - **Magnetic field measurements have been performed at Fermilab on 1.5 m magnetic length model dipoles for the Superconducting Supercollider. Harmonic measurements are recorded at room temperature before and after the collared coil is assembled into the yoke and at liquid helium temperature. Measurements are made as a function of longitudinal position and excitation current. High field data are compared with room temperature measurements of both the collared coil and the completed yoked magnet and with the predicted fields for both the body of the magnet and the coil ends.**

I. INTRODUCTION

Several short model magnets of 50 mm aperture have been built as part of Fermilab's contribution to the SSC dipole development effort [1]. The performance of these magnets has been evaluated throughout construction as well as during cryogenic operating conditions. We present here the results of the magnetic field measurements. Mechanical and quench performance of 50 mm aperture magnets are discussed in contributed papers at this conference [2,3].

II. EXPERIMENTAL DETAILS

A. *Definition of Harmonic Coefficients*

The magnetic field inside the magnet aperture can be described by the following equation:

$$B_y - iB_x = B_o * 10^{-4} \sum_{n=0} (b_n - ia_n) * ((x+iy)/r_o)^n \qquad (1)$$

where B_x and B_y are the x and y components of the field, B_0 is the dipole field, and a_n and b_n are the skew and normal coefficients. These coefficients are dimensionless but depend on the chosen value of the reference radius r_o. For the SSC dipoles, this radius is 10 mm. The x and y directions are chosen so that the skew dipole term a_o is zero.

B. *Room Temperature Measurements*

Magnetic measurements for collared coil assemblies and completed coldmass assemblies were performed at the Magnet Test Facility at Fermilab using the BNL Mole measuring system[4]. The Mole probe consists of tangential plus bucking coils of active length 0.6 m. The probe was rotated at 0.31 Hz and the resultant voltages were read by fast sampling DVM's and recorded on a HP236 computer for online FFT analysis. Probe centering was possible through elimination of the 16-pole which results primarily through feeddown from the allowed 18-pole. Data were recorded at ± 10 A (to eliminate the effects of the earth's magnetic field and any local magnetization of surroundings) at several positions along the length of the magnet.

C. *Cold Measurements*

Once the completed coldmass passed all room temperature mechanical and electrical inspections, it was tested in the 3.6m vertical dewar located at the Fermilab Superconducting Magnet R&D facility. The dewar was instrumented with pressure transducers and liquid level gages. The magnet stainless steel shell was instrumented with carbon and platinum thermometers. Magnet current was supplied by two Transrex 500-5 power supplies capable of generating currents in excess of 10 kA.

Magnetic measurements were performed with room temperature probes inserted into an anti-cryostat which in turn was inserted into the bore of the magnet. The anti-cryostat consisted of two concentric stainless steel tubes. The annulus separating the tubes was filled with superinsulation and evacuated to minimize heat leaks.

The dipole field strength was measured with a Rawson-Lush 789 field meter. The probe was a precision rotating coil of active length 6.35 mm. The meter produced an analog output which was proportional to the field strength.

Field harmonics up to the 12-pole were recorded using a multiple winding Morgan coil probe[5] of length 0.46 m. The probe was rotated at 6 Hz and the resultant voltages were processed through a V/F converter-based magnetometer. Data from the magnetometer were controlled through CAMAC bus

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by a DEC MicroVax II computer. The MicroVax can process magnetometer data at a maximum rate of 3 Hz. Since the 16-pole cannot be measured using this Morgan coil, probe centering was not possible. We therefore report only the normal sextupole (b_2) and normal decapole (b_4) which are not subject to significant feeddown corrections.

All of the tests reported here were performed in atmospheric pressure boiling liquid helium (4.2K). After the transfer function was measured using the Rawson-Lush probe, the Morgan coil was used to measure magnetic fields as a function of longitudinal position and excitation current using the waveform shown in Fig. 1. The magnet was first ramped to quench in order to erase its persistent current history. The magnet was then ramped at 12 A/s to 200 A below the previously established quench plateau current (I_q -200A), then down to 110 A and then up to 5000 A in order to simulate the magnetization history from a typical accelerator cycle. At 5000 A, magnetic measurements were made at approximately 50 mm intervals along the length of the magnet. Then the magnet was ramped to 5500 A then down to 5000 A to change the orientation of the persistent currents, then another set of longitudinal measurements were made. Finally, the magnet was ramped down to 100 A then up to I_q -200A then back down to 100 A and up to 1000 A, all at 16 A/s. Magnetic measurements were recorded as a function of excitation current starting at 500 A on the up-ramp to the end of this final waveform.

In addition to these standard magnet evaluation tests, remnant field measurements were performed on one 50 mm magnet (DSA321). The magnet was ramped under various excitation waveforms, and the dipole strength as a function of longitudinal position was recorded using the Rawson-Lush field meter.

III. RESULTS

Table I summarizes the harmonics at 10 A, room temperature for magnets DSA321, DSA323, and DSA324. For magnet DSA321 the room temperature harmonics were

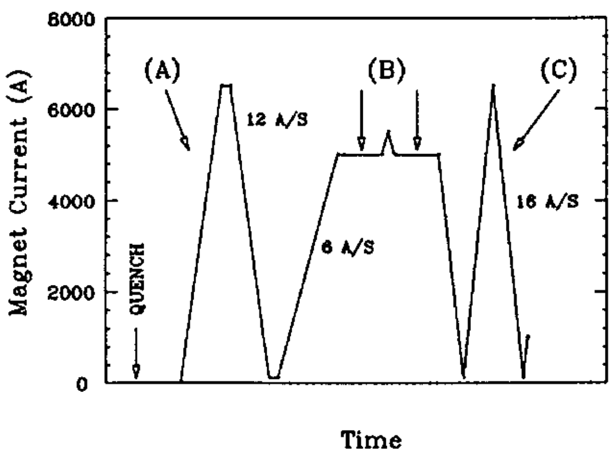

Fig. 1. Waveform used for 4.2 K magnetic measurements after a quench to erase persistent current history. (A) pre-ramp cycle to establish persistent currents, (B) dwells at 5000 amps for longitudinal field map, (C) at magnet's longitudinal center, ramp cycle for magnetic field as a function of excitation current.

measured after cold testing; however, no significant change in room temperature harmonics before and after cold testing has been seen in any of the Fermilab model magnets.

For each harmonic value in the table, the average and R.M.S. of the harmonic over ± 250 mm relative to magnet center are given. This R.M.S. contains random measurement errors as well as deviations due to magnet construction errors. The quoted random error is estimated from successive readings at one longitudinal location in the magnet body field of DSA324. With the exception of b_1, a_1, and a_2, the R.M.S. is consistent with measurement uncertainty. For b_1, a_1, and a_2, we observe systematic changes along the body of the magnet. The SSC systematic and random tolerances for each harmonic during operation at 4.35 K are provided for comparison.

DSA324 differs from DSA321 and DSA323 in the amount of Kapton pole shimming[2]. For DSA324, the nominal Kapton pole shimming was increased by 0.13 mm in the inner coil and decreased by 0.13 mm in the outer coil. The value of b_2 was expected to decrease by .09 units, while b_4 was expected to decrease by .16 units with respect to the nominal value[7]. DSA324 shows the expected deviation of b_2 and b_4 from DSA321. However b_2 and b_4 for DSA323 also differ from DSA321 values so it is difficult to draw any quantitative conclusions.

TABLE I
ROOM TEMPERATURE HARMONICS (UNITS @ 10 mm)

Pole	321	323	324	324 Ran.	SSC Sys.	SSC Ran.
b2	2.96	0.91	1.8	0.025	0.8	1.15
	±.12	±.06	±.08			
b4	0.36	0.23	0.18	0.029	0.08	0.22
	±.02	±.02	±.02			
b6	-0.07	-0.05	-0.04	0.007	0.01	0.02
	±.01	±.00	±.01			
b8	0.05	0.05	0.02	0.007	0.02	0.01
	±.01	±.00	±.02			
b10	0.02	0.02	0.02	0.001	–	–
	±.00	±.00	±.02			
b1	-0.05	0.09	0.15	0.09	0.04	0.5
	±.21	±.18	±.17			
b3	-0.04	0.02	-0.01	0.04	0.03	0.16
	±.03	±.04	±.02			
b5	0.01	-0.01	-0.02	0.017	0.02	0.02
	±.01	±.01	±.01			
b7	0.	0.	0.	0.	0.01	0.01
	±.00	±.00	±.00			
a1	-2.1	-0.09	-0.12	0.13	0.04	1.25
	±.32	±.29	±.23			
a2	0.05	0.16	0.24	0.04	0.03	0.35
	±.04	±.14	±.10			
a3	0.05	-0.11	0.17	0.03	0.03	0.32
	±.05	±.05	±.03			
a4	0.06	0.01	0.06	0.025	0.02	0.05
	±.04	±.03	±.02			
a5	0.01	-0.01	0.04	0.014	0.02	0.05
	±.02	±.01	±.01			

Table II shows the measured and predicted[6,7] transfer functions for the two 50 mm dipoles that have been cold tested. For both magnets, the 10 A collared coil and completed coldmass transfer functions are in agreement with prediction. At 5000 A, a decrease in the transfer function is observed, as expected, due to iron saturation. Measured values at 5000 A are slightly lower than predicted.

The correlation between the first two allowed harmonics (b_2,b_4) for room temperature collared coils at 10 A, room temperature completed coldmasses at 10 A, and 4.2 K completed coldmasses at 5000 A are shown in Fig. 2. There is an average increase in sextupole (b_2) of 4 units from collaring to yoking. There is a smaller change in b_2 from room temperature to 4.2 K, 5000 A operation, and most of this change can be attributed to iron saturation. The decapole (b_4) decreases in both yoking and cold testing at 5000 A. Note that DSA323 satisfies both the b_2 and b_4 SSC tolerances.

Fig. 3 shows b_2 with a transport current of 4880 amps. The horizontal axis represents the center of the 0.46 m Morgan coil with respect to the longitudinal center of the magnet (positive value data points are towards the magnet lead end). The vertical axis represents the average value of b_2 over the 0.46 m Morgan coil. These data are recorded during part (B) of the waveform illustrated in Fig 1. There is a decrease in b_2 of approximately 0.3 units on the lead end side of the magnet center. This is due to the magnetization at cryogenic temperatures of the strain gage transducers[8]. The rise in b_2 followed by a -4 unit decrease starting at -0.41 m represents the transition between the straight section and the beginning of the return end. The value of integral b_2 in the return end can be inferred from the data taken in the end region after correcting for the part of the 0.46 m probe that is still in the magnet body field. We calculate this end field b_2 to be -15± 1 units. This is in very good agreement with the predicted value of -15.4 units [9]. The observed asymmetry between return and lead ends is most likely due to the magnet leads.

The dependence of b_2 on superconductor and iron magnetization is illustrated in Fig 4. These data were recorded during part (C) of the waveform as shown in Fig. 1. The up-down asymmetry in both DSA321 and DSA323 at low currents is largely due to the aforementioned magnetized strain gage transducers. While the shape of the two b_2 distributions are similar, DSA321 has a more positive geometric sextupole. In general, this magnet has larger harmonic amplitudes than the other 50 mm magnets as shown in Table I and Fig. 2.

At high currents iron saturation effects can be observed. The calculated b_2 due to iron saturation in Fig. 4(III) shows a variation of approximately 0.6 units between 4500 A and

TABLE II
TRANSFER FUNCTION FOR 50 mm MAGNETS
(T/kA)

	DSA321	DSA323	Predicted
Collared Coils ± 10 A	0.795	0.794	0.795
Yoked ± 10 A	1.043	1.043	1.045
Cold at 5 kA	1.036	1.033	1.040

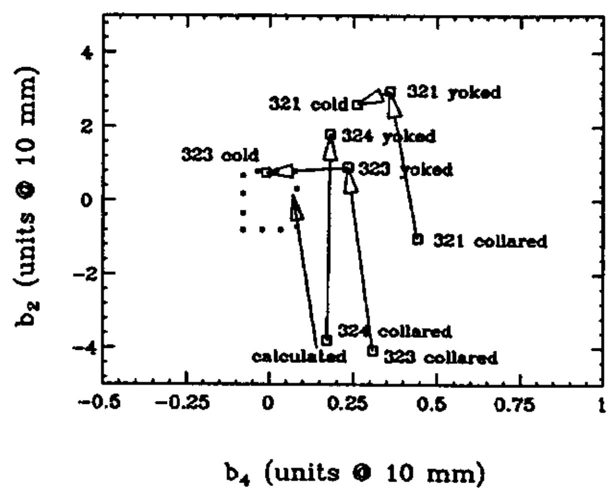

Fig 2. Correlation between b_2 and b_4 for room temperature collared coils and completed coldmasses at 10 A, and 4.2 K completed coldmasses at 5000 A compared to prediction. Box enclosed by dots represents the systematic tolerances for b_2 and b_4 for the collider dipole.

7000 A[6]. The measured variation in DSA321 and DSA323 is even smaller than predicted. The shape of b_2 at high field is controlled by cutting notches in the yoke midplane to counteract the effect of iron saturation in the poles. Further improvements in minimizing the change in b_2 due to iron saturation may be possible by optimizing the size and location of these cutouts.

The longitudinal dependence of the dipole remnant field has been measured on one 50 mm dipole (DSA321). The magnet was pre-ramped at 100 A/s to various excitation currents as shown in Fig. 5. The observed periodic behavior has been found in other superconducting magnets[10]. The period of the dipole field is measured through Fourier transform to be 96.5 +/-6 mm. This is to be compared with the inner and

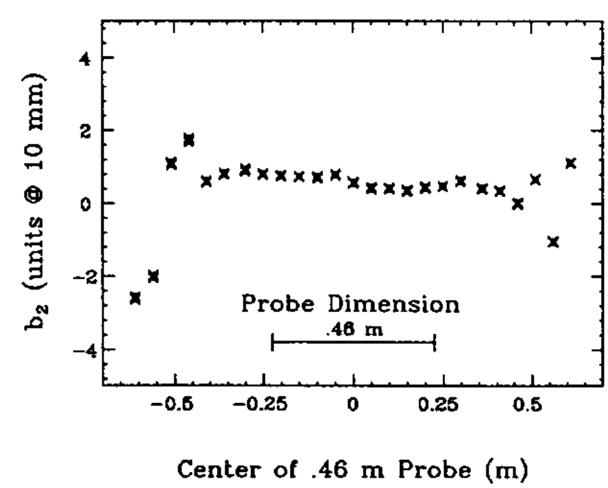

Fig 3. b_2 averaged over 0.46 m coil vs position of probe center with respect to magnet center for up-ramp portion of part (B) of waveform (See Fig. 1).

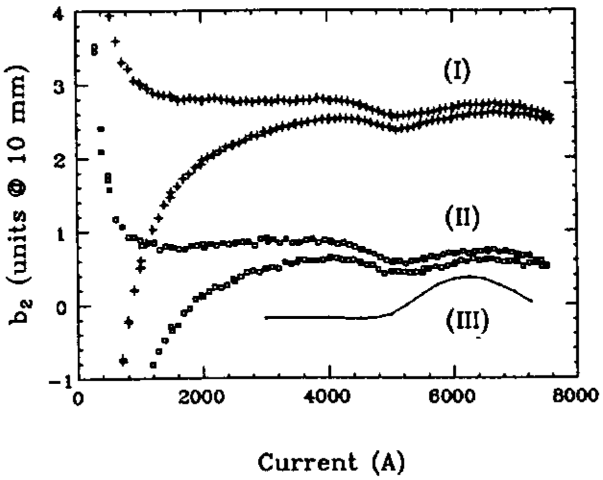

Fig. 4. b_2 as a function of excitation current for (I) DSA321, (II) DSA323, (III) predicted iron saturation.

outer twist pitch (86 and 93 mm, respectively). The amplitude of the periodic dipole grows with increasing maximum pre-ramp current[11]. Tests performed on a 40 mm magnet (DS0315) show a periodicity of 75.3 mm compared to 74 mm and 76 mm twist pitch for inner and outer coils[12].

For the 7000 A pre-ramp excitation, we have measured the time dependence of the remnant field amplitude. (See Table III.) The time dependence is non-linear, with a larger decrease in amplitude in the first 4 hours.

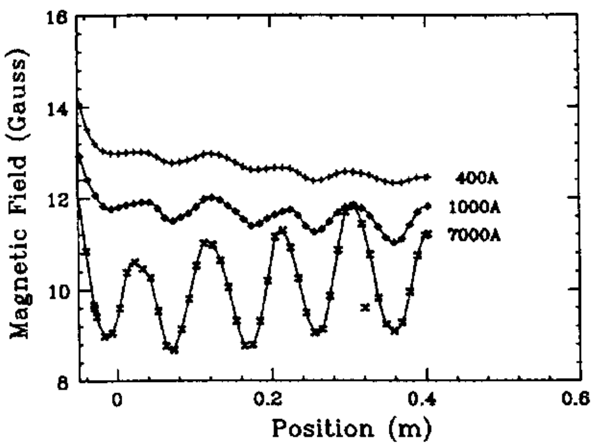

Fig. 5. Remnant field as a function of longitudinal position (referenced to magnet center) for various pre-ramp excitation currents.

TABLE III
REMNANT FIELD AMPLITUDE VS. TIME

Time (Hours from end of excitation cycle)	Amplitude (Gauss)
0.5	1.25
4.0	0.78
23.0	0.58

IV. CONCLUSION

Magnetic measurements have been completed on 50 mm aperture 1.5 meter dipoles. The effects of yoking and cold testing agree well with predictions. One of the two cold tested dipoles satisfies the SSC specification for sextupole/decapole. Several magnets of the same design will be tested this year in order to measure the R.M.S. distribution of the multipole harmonics.

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